



# **Knowledge Based Reliability Evaluation of New Package Technologies Utilizing Use Conditions**

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# INTRODUCTION

This White Paper describes a process for using “use conditions” as the basis for validating the reliability of package technologies. This approach is based on an understanding of failure mechanisms and the end user conditions expected to be encountered by the package. Based on the expected end use of the package, a reliability stress program is determined and all failure mechanisms encountered are evaluated to establish relevance and to validate acceleration and models.

## SCOPE

This process will be applied to new package or assembly technologies. Modifications and extensions of existing technologies can also benefit from this method if the use conditions for the existing technology are known.

## REFERENCE DOCUMENTS

EIA/JEP122: Failure Mechanisms and Models for Silicon Semiconductor Devices

ESD 34: Failure Mechanism Driven Reliability Qualification of Silicon devices

## TABLES AND APPENDICES

Appendix A:	Use Condition Reliability Validation Process Flow
Appendix B:	Acceleration Models
Table 1:	Common Acceleration Models
Table 2:	Typical Values for Some Common Failure Mechanisms
Appendix C:	Application Examples

## PROCEDURE

A flowchart of this procedure is contained in Appendix A. The following paragraphs describe each step in the flow.

### I. Definition of Environmental, Lifetime, and Manufacturing Conditions

This is one of the most critical steps in the process as it provides the basis for all follow on activities. Decisions made at this point will be utilized at all future steps. Determining the target market segment establishes the use environment and lifetime appropriate for the technology. There may be significant overlap as products may be sold into more than one market, necessitating a testing envelope that encompasses all of the relevant markets (environment/lifetime). The basic PC based market segments are:

- Desktop
- Server, Workstation
- Notebook
- Combinations of any or all of the above

As each market segment can have various failure rate requirements, the cumulative failure rate goals at end of life need to be defined.

## II. Determination of Speculative Reliability Stresses:

The goal of this step is to establish a set of initial reliability stresses for use in collecting failure mechanism data. Since this and following steps may require modeling and data interpretation, a team of content experts is formed. The team will include Quality/Reliability Engineering, Materials Engineering, Design, Numeric Model Expert(s), and Silicon Reliability Engineers (if the technology could have an interaction with the silicon technology).

This step can be divided into a number of activities.

**IIA).** Bound the accelerated reliability stress conditions so that they aren't set beyond the physical capability of the assembly materials. These physical limits may put upper and/or lower limits on the testing regime. The material property data are also used for establishing the global stress models. Typical material property data needed includes:

- CTE
- Modulus as a function of temperature
- Elongation as a function of temperature
- Creep properties
- Glass transition temperature

**IIB).** Determine which stresses are required to accelerate each of the market segment environments using the data gathered in steps I and IIA. The most commonly used stresses are:

- Temperature cycling (air to air cyclic stress)
- Thermal shock (liquid to liquid cyclic stress that can be more severe than temperature cycling. It has very fast ramp rates and shorter cycle times than temperature cycle.)
- Temperature, Humidity and Bias (THB)
  - 85 °C/85% RH (non-condensing and run at atmospheric pressure)
  - Highly Accelerated Stress Test (HAST) Combines high temperature with humidity (typically 85% RH) in a non-condensing atmosphere (requires a pressure vessel)
- Pressure Cooker (PCT) - unbiased with conditions of 121 °C/100% RH (requires a pressure vessel)
- Power cycling (non accelerated)
- Shock (non accelerated)
- Vibration (non accelerated)
- Preconditioning (non accelerated)

**IIC).** Determine whether there are any new requirements or uses that may require a new stress type. Two examples of this are “mated pair” testing where the component may need to be tested in a socket because the stress state changes due to socket/component interaction and preconditioning which simulates moisture uptake and high temperature solder reflow as seen during customer (OEM) manufacturing.

**IID).** Develop global, numeric stress models for the package. These models should be used to determine if there are any high stress areas in the package which might require special attention and evaluation. Areas identified should be evaluated pre and post environmental stress testing to determine if there is a potential reliability impact on devices that might not be found with standard electrical tests. Evaluations could consist of visual, cross sections, CSAM, etc., in addition to electrical test.

**IIE).** Determine all known and possible issues and failure modes that may impact the technology. Use knowledge from existing similar technologies as a source of possible mechanisms and failure types. If there are analogs from prior history then use those available acceleration models and values as the starting point. Perform a literature search to determine possible mechanisms and acceleration values that may be unique to the new technology or material set. For mechanisms with no precedents, select a conservative acceleration factor for planning purposes until data are available. Develop a table of issues and “best known” accelerations. Table 1 in appendix B contains a table and description of commonly used acceleration models.

**II F).** Use standard models with the acceleration factors, environmental conditions, material property data, and lifetime requirements to develop a set of speculative reliability stresses. These speculative reliability stresses will be used until adequate data are available for recalculating acceleration factors. As noted in IIA, ensure hot and cold temperature extremes of the stress do not exceed the physical capability of the material set in the package.

Other factors to consider when setting speculative conditions:

- Test socket compatibility with test conditions
- In situ monitoring of DUT's
- Whether a guardband is to be built into the speculative (and/or final) reliability stress conditions for the technology
- How the stressing needs to be accomplished:
  - Stand alone component
  - Surface mounted to a board
  - In a socket
  - With heatsink attached
  - Any combinations above

Select conditions that yield the fastest throughput time and are compatible with the package material set.

### **III. Determine Overstress Conditions**

Define overstress conditions as part of the stress model development. These are derived from the estimated acceleration factors and represent conditions that simulate extremely long lifetimes in a highly accelerated fashion. Overstress conditions are used to define technology margins, determine acceleration factors, and identify all failure mechanisms. Subsequent failure model development will determine the relevant mechanisms. Overstress condition data can also be used for the mechanism modeling activities.

### **IV. Apply Data to Models**

Following completion of experiments using speculative and overstress conditions, prepare Pareto charts of the failure mechanisms and apply existing models to those mechanisms already understood. Check existing models and mechanisms for differences from predictions and determine if the technology follows a new acceleration curve. Compare package failure mechanisms and locations to model predictions. Analyze discrepancies between models and data and use this information to close gaps in the models. These models will be required for making extrapolations to different form factors or to other technologies as noted in step II, and thus, need to be accurate.

Recalculate acceleration factors and develop models for extrapolation to other stresses and/or environments

Determine which mechanisms don't meet lifetime expectations. Mechanisms not meeting the lifetimes need to be studied and plans for resolution developed.

### **V. Determine Final Reliability Stress Conditions**

Based on use conditions and the data generated in step IV, calculate the final reliability stress conditions and durations. Subsequent testing and technology goals will be based on these stresses. Select conditions that give the fastest throughput time but that are still compatible with the materials to maximize the number of data turns available for data collection. Also consider factors such as test socket compatibility with the test conditions and possible in situ monitoring of DUT's.

## VI. Establish Baseline Performance

Establish the technology's baseline performance using the final reliability stress conditions and durations. Stress sample sizes need to be consistent with the end of life failure rate expectations. Failure mechanisms may occur during reliability stressing that are irrelevant due to large acceleration factors and need to be discounted (invalidated) when making failure rate calculations. Utilize the data from step III to assist these decisions. Irrelevant failure modes need to be documented thoroughly in any case, as they should be explained in the final technology documentation. Changes to the technology (materials, processes) need to be compared to the existing baseline. Deviations from the baseline need to be validated against the model for impact to lifetime predictions.

### Data collection

Reliability stress data can be collected in several ways. Typically the data are binomial data sets (pass/fail) and are censored, that is, the readouts are performed at discrete intervals (hours or cycle counts). Variables (or parametric) data look at a measured variable of the DUT (temperature sensor output e.g.). Both types of data can be collected either at discrete intervals or continuously during the stress. Continuous variables data are the most useful types of data and should be used where ever possible. Examples include;

Binomial data types (pass/fail):

- Shorts
- Opens

Variables (parametric) data types (measured or continuous):

- Electrical leakage
- Temperature
- Weight gain/loss
- Crack length, density, count
- Solder joint strength
- Capacitance
- Resistance
- Material property changes
- Warpage
- Percent delamination
- Void density/count

### Technology Extensions

Changes that extend the existing technology to encompass new factors such as package form factor (size), die size or silicon technology may all be extensions. There are two ways to certify an extension; 1) collect additional data or 2) extrapolate from existing models.

Collecting additional data requires that units of the appropriate form factor be built and submitted for reliability stressing. However, it is not critical that all stresses be applied. Conduct an assessment to evaluate the changes being made and the possible risks to the base technology. Utilize the learning from the base technology evaluation. Consider reconvening the team of experts identified in Step II. Only apply those stresses where the assessment suggests there is an increase in risk. Typically, changes in form factors require thermomechanical stressing only as the change in die or package size might change the package stresses. Changes in package materials or process changes may require moisture stressing as well as thermomechanical stresses.

# DATA REPORTING

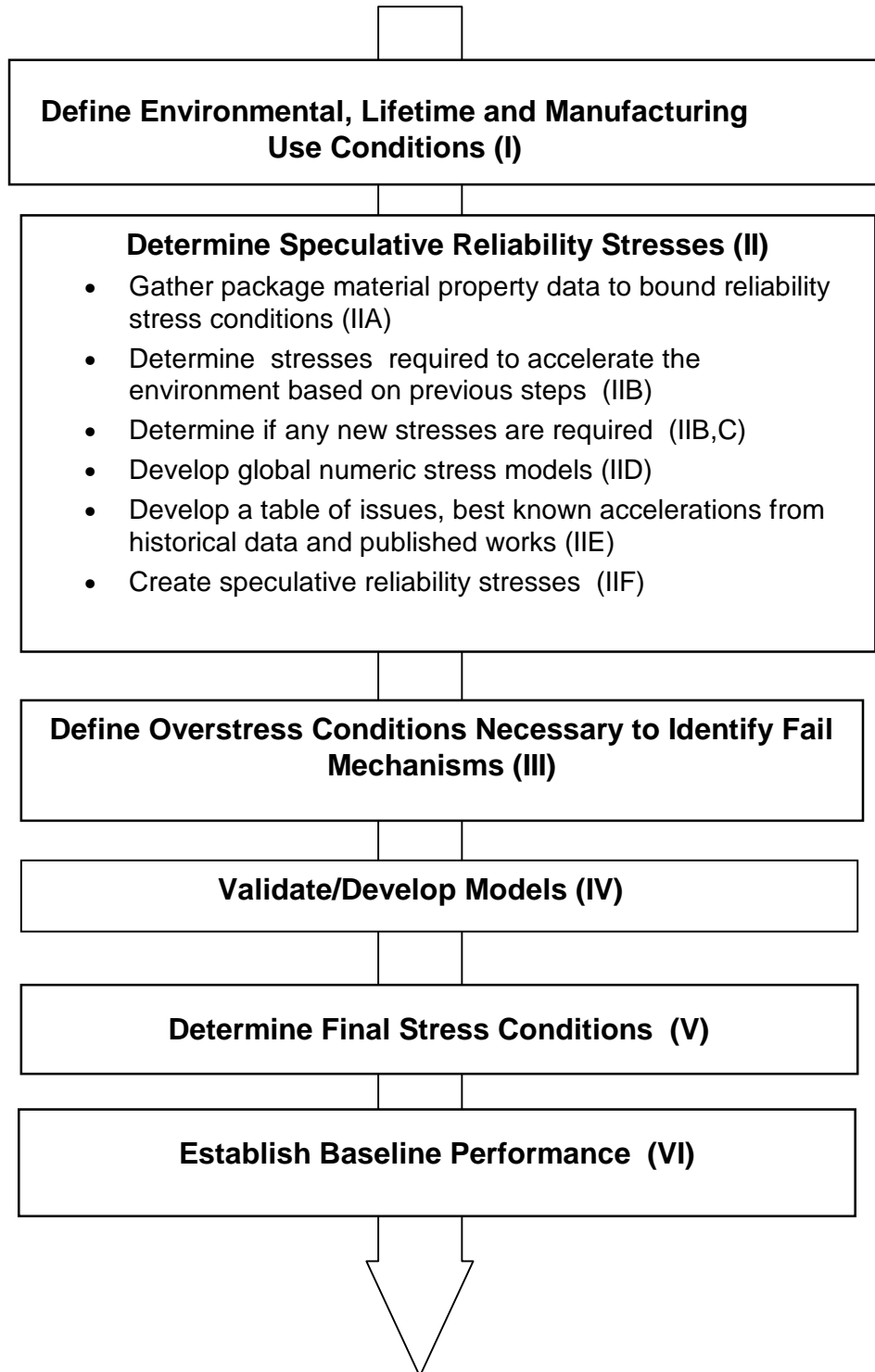
Data generated during a technology / package certification is considered Intel proprietary. Data available to customers will follow current practices.

The internal Technology / Package Report should contain:

- Certified technology description (envelope)
- Performance to final reliability stress conditions
- Use condition assumptions
- Extrapolated (or actual) lifetime margins against use conditions
- Performance to final reliability stress conditions
- Sample sizes
- Detailed mechanism assessments and models with extrapolations to technology limits
- Acceleration factors and model coefficients
- Model and key model parameters determined from data
- Summary of all failure mechanisms, both relevant and irrelevant.
- Durations for lifetime endpoints
- Failure rate goals

## APPENDIX A

### Use Condition Reliability Validation Process Flow





## Appendix B

### Acceleration Models

Table 1 is a list and description of commonly used acceleration models. Other sources for this type of information are EIA/JEDEC document EIA/JEP122 “Failure Mechanisms and Models for Silicon Semiconductor Devices”, Symposium Proceedings, and internal company historical data.

## TEMPERATURE/HUMIDITY MECHANISMS

Peck’s model is typically used but there are several other models that have demonstrated success at modeling the impact of RH on failure mechanisms. Other models should be considered when calculating lifetimes. When making the calculations be sure that only the failure mechanism of interest is used when plotting failure rates (that is, don’t mix opens failures for package vias with shorts failures for copper migration, they need to be modeled independently).

Data need to be collected at least at a minimum of two different temperatures (at constant RH) or four conditions if RH modeling is being performed and preferably more.

The failure rate data are plotted  $1/T(\text{Kelvin})$  vs. log time, the slope of which is the activation energy for the mechanism. The offset in the curves when multiple RH’s are used is the effect due to RH. These data can then be used in the model to calculate the expected time to failure at the target use condition temperature and humidity.

Alternatively the plotted data can be extrapolated and estimates made graphically which has the advantage that discontinuities in the data (two slopes e.g.) become readily apparent. Discontinuities would suggest that there is a change in the mechanism possibly due to changes in the material properties. This can result in inaccurate lifetime assessments but can also be utilized to collect data on this mechanism even more rapidly. In this situation caution is urged.

## TEMPERATURE ACTIVATED MECHANISMS

Typically these require only an Arrhenius model. When making the calculations be sure that only the failure mechanism of interest is used when plotting failure rates (that is, don’t mix opens failures with shorts failures, they need to be modeled independently).

Data need to be collected at least at a minimum of two different temperatures and preferably more. The failure rate data are plotted  $1/T(\text{Kelvin})$  vs. log time, the slope of which is the activation energy for the mechanism

These data can then be used in the model to calculate the expected time to failure at the target use condition temperature and humidity.

Alternatively the plotted data can be extrapolated and estimates made graphically which has the advantage that discontinuities in the data (two slopes e.g.) become readily apparent. Discontinuities would suggest that there is a change in the mechanism possibly due to changes in the material properties. This can result in inaccurate lifetime assessments but can also be utilized to collect data on this mechanism even more rapidly. In this situation caution is urged.

## TEMPERATURE/VOLTAGE MECHANISMS

These typically follow an Eyring model with a term for the voltage acceleration portion of the model in front of the exponential term. Although not used extensively in packaging, they are discussed for completeness. There are numerous models describing voltage/temperature mechanisms. This one (Eyring) is generic and specific mechanisms need to be handled separately. Similar to the THB models (Peck’s e.g. is an Eyring derived model) they are analyzed similarly.

Data need to be collected at least at a minimum of two different temperatures (at constant voltage) or four conditions if voltage modeling is being performed and preferably more. The failure rate data are plotted  $1/T(\text{Kelvin})$  vs. log time, the slope of which is the activation energy for the mechanism. The offset in the curves

when multiple voltages are used is the effect due to voltage. These data can then be used in the model to calculate the expected time to failure at the target use condition temperature and voltage.

Alternatively the plotted data can be extrapolated and estimates made graphically which has the advantage that discontinuities in the data (two slopes e.g.) become readily apparent. Discontinuities would suggest that there is a change in the mechanism possibly due to changes in the material properties. This can result in inaccurate lifetime assessments but can also be utilized to collect data on this mechanism even more rapidly. In this situation caution is urged.

## THERMOMECHANICAL MECHANISMS

Typically these failures are modeled using a Coffin-Manson relationship. There are some key assumptions that go into the success of this type of model, specifically, that the materials under consideration behave more or less linearly over the test range of interest. Thermal cycling and temperature shock are treated the same.

Data need to be collected over at least three temperature ranges, two of which have the same  $\Delta T$  and at least one which is larger. This is required so that the model can be calibrated relative to the neutral temperature of the package. The neutral temperature is the temperature where the package stresses go to zero and is generally in the range of the mold compound or epoxy underfill cure temperatures. This assumption needs to be validated with moiré warpage data on completely processed packages.

Temperature cycling data may be impacted by the dwell times at both the highest and lowest temperatures in the cycle. This is especially true when dealing with creep type mechanisms (solder joints e.g.). Therefore, it is necessary to include stress legs that have a long dwell time. These data need to be analyzed with the short dwell legs to determine the impact of dwell on performance.

Failure rate curves as a function of cycle counts and stress condition need to be developed for each of the thermomechanical failure modes. The slope of Log-log plots of the mean time to failure for each of the conditions is the Coffin-Manson coefficient for that mechanism.

If the data don't appear to be well behaved then the data need to be reanalyzed using the neutral temperature as the hot side of the temperature cycle for all of the stress conditions. This is likely to be true when the mechanism of interest doesn't exhibit significant stress relaxation during the stress cycle (brittle materials e.g.). Solders are likely to experience stress relaxation and will likely model using only the stress  $\Delta T$ . This is not a hard and fast rule and both analyses should be performed.

**Table 1**  
**Common Acceleration Models**

Mechanism	Model	Assumptions
Temperature, Humidity mechanisms	<p>Peck's</p> $TF = A_0 \times (a+bV) \times RH^N \times \exp[E_a/kT]$ <p>AF (ratio of TF values, Stress/use) = <math>\frac{[(a+bV_{Stress})/(a+bV_{Use})]}{\exp[(E_a/k)(1/T_{Stress}-1/T_{Use})]} \times (RH_{Stress}/RH_{Use})^{-N}</math></p>	<ul style="list-style-type: none"> <li>• AF = acceleration factor</li> <li>• TF = time to failure,</li> <li>• <math>A_0</math> = arbitrary scale factor</li> <li>• V = Bias voltage (drops out with constant bias)</li> <li>• RH = Relative Humidity as (at constant RH this factor drops out)</li> <li>• N = an experimentally determined constant</li> <li>• <math>E_a</math> = activation energy for the mechanism (0.75 is conservative)</li> <li>• k = Boltzmann's constant = <math>8.625 \times 10^{-5}</math> eV/°K,</li> <li>• T = Temperature in °Kelvin,</li> <li>• There are other models used for THB mechanisms which should be checked for fit to the data</li> </ul>
Thermal Effects	<p>Arrhenius</p> $TF = A_0 \times \exp[E_a/kT]$ <p>AF (ratio of TF values, Bake/use) = <math>\exp[(E_a/k)(1/T_{Bake}-1/T_{Use})]</math></p>	<ul style="list-style-type: none"> <li>• AF = acceleration factor</li> <li>• TF = time to failure,</li> <li>• <math>A_0</math> = arbitrary scale factor</li> <li>• <math>E_a</math> = activation energy for the mechanism (0.75 is conservative)</li> <li>• k = Boltzmann's constant = <math>8.625 \times 10^{-5}</math> eV/°K,</li> <li>• T = Temperature in °Kelvin,</li> </ul>
Temperature & Voltage Mechanisms	<p>Eyring</p> $TF = A_0 \times V^N \times \exp[E_a/kT]$ <p>AF (ratio of TF values, Stress/use) = <math>\frac{(V_{Stress}/V_{Use})^N}{\exp[(E_a/k)(1/T_{Stress}-1/T_{Use})]}</math></p>	<ul style="list-style-type: none"> <li>• AF = acceleration factor</li> <li>• TF = time to failure,</li> <li>• <math>A_0</math> = arbitrary scale factor</li> <li>• V = Voltage but may include terms for field strength e.g.</li> <li>• N = an experimentally determined constant for Voltage (at constant V this factor drops out)</li> <li>• <math>E_a</math> = activation energy for the mechanism</li> <li>• k = Boltzmann's constant = <math>8.625 \times 10^{-5}</math> eV/°K,</li> <li>• T = Temperature in °Kelvin</li> <li>• There are numerous models describing voltage/temperature mechanisms. This one is generic and specific mechanisms need to be handled separately.</li> </ul>
Thermo-mechanical mechanisms	<p>Coffin-Manson</p> $N_f = C_0 \times (\Delta T)^{-1/c}$ <p>AF (ratio of <math>N_f</math> values per stress cycle, automotive/office) = <math>N_{Stress}/N_{Use} = (\Delta T_{Stress}/\Delta T_{Use})^{-1/c}</math></p>	<ul style="list-style-type: none"> <li>• AF = acceleration factor</li> <li>• <math>N_f</math> = Number of cycles to failure,</li> <li>• <math>C_0</math> = a material dependent constant,</li> <li>• <math>\Delta T</math> = entire temperature cycle-range for the device,</li> <li>• <math>\Delta T_0</math> = the portion of the temp. range in the elastic region,</li> <li>• <math>1/c</math> = an empirically determined constant (Coffin-Manson exponent) with <math>0 &lt; c &lt; 1</math>. C = 0.67 would be conservative.</li> <li>• Assumes that the stress and use ranges remain in the elastic regime for the materials</li> <li>• The Norris Landzberg modification to this model takes into account the stress test cycling rate</li> </ul>
Creep	$TF = B_0 (T_0 - T)^{-n} \exp(E_a/kT)$ <p>AF (ratio of TF values, accelerated/use) = <math>\frac{(T_0 - T_{Use})^n}{(T_0 - T_{Accel})^n} \times \exp[(E_a/k)(1/T_{Accel}-1/T_{Use})]</math></p>	<ul style="list-style-type: none"> <li>• AF = acceleration factor</li> <li>• TF = time to failure,</li> <li>• <math>B_0</math> = process dependent constant,</li> <li>• T = temperature in °Kelvin,</li> <li>• <math>T_0</math> = stress free temperature for metal (~ metal deposition temperature for aluminum)</li> <li>• <math>n = 2 - 3</math>, (n usually ~5 if creep, thus implies <math>T &lt; T_m/2</math>)</li> <li>• <math>E_a</math> = activation energy = 0.5 - 0.6eV for grain-boundary diffusion, ~ 1 eV for intra-grain,</li> <li>• k = Boltzmann's constant = <math>8.625 \times 10^{-5}</math> eV/°K</li> </ul>

Mechanism	Model	Assumptions
On-off/Power Cycling	Na	<ul style="list-style-type: none"> <li>Power cycling is a non-accelerated stress and may in fact overlook creep induced mechanisms due to the short well typically used in the testing.</li> </ul>
Drop	Na	<ul style="list-style-type: none"> <li>Non-accelerated. Testing is usually done in increasing increments until failure is observed</li> </ul>
Vibration	Na	<ul style="list-style-type: none"> <li>Non-accelerated.</li> </ul>

## PHYSICAL MODELS

Once an acceleration model is established the data needs to be checked against physical models for failure mechanisms. That is, the calculated activation energies or Coffin-Manson coefficients need to make physical sense relative to the mechanism they describe. Corrosion for example may be expected to be in the 0.5 to 1.0 eV and diffusion in the 1.1 eV ranges. Large or small values should be carefully analyzed to insure that there aren't competing mechanisms or a change in the physical properties of a material that significantly changes the slope of the acceleration curve. Modeling to the physical models should take precedence over polynomial curve fits as the former more closely links to the physical mechanism.

Table 2 gives some typical values for physical mechanisms (for reference only). New technologies must have accelerations calculated for each mechanism or data indicating acceptable substitution from a prior technology.

**Table 2**

**Typical Values for Some Common Failure Mechanisms**

	Ea (activation energy ranges in electron volts)	Other Coefficients
Peck's	0.75-1.5 eV (Dependent on the materials used for each package type)	N = 2 - 12 (dependent on the materials used for each package)
Arrhenius	0.3 - 0.6 Electrolytic corrosion 0.5 - 0.9 Electromigration in Al 0.6 - 1.0 Corrosion in THB 0.9 - 1.8 Metal Migration 0.9 - 1.5 Diffusion	<b>Na</b>
Coffin-Manson	Na	c = 0.1 - 0.3 brittle materials 0.4 - 0.6 ductile materials 0.5 - 1.0 hard metals
Creep	0.5 - 1.0 eV	N = 2 - 3 for solder

## Non accelerated stresses

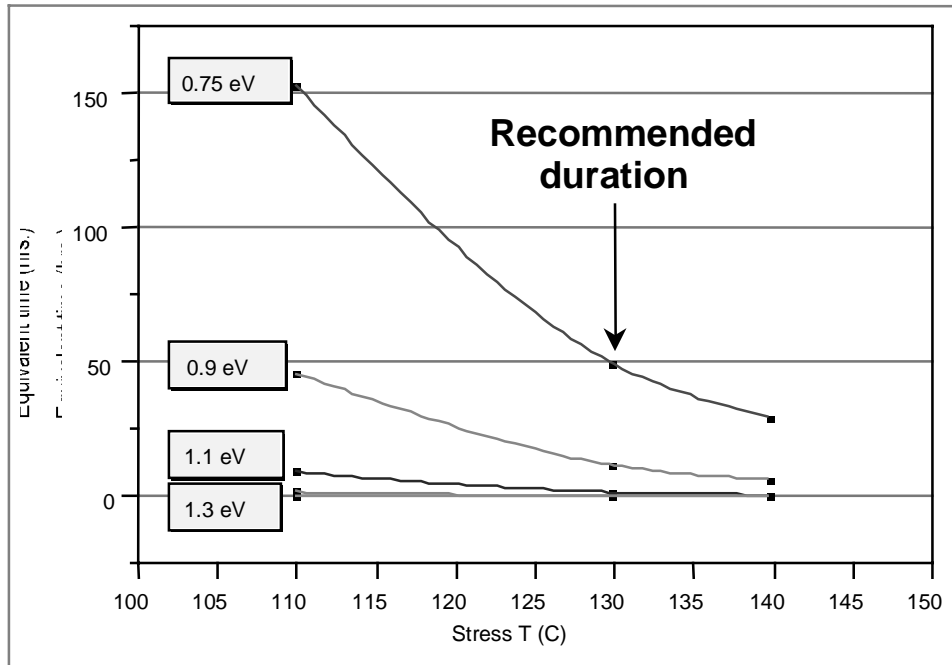
### POWER CYCLING

Power Cycling is simply on/off testing of the part and should be considered when evaluating packages that are expected to dissipate high power. In this test the unit is cycled from room temperature up to the junction temperature specified for the particular technology with the thermal solution in place. Establish the upper temperature that a unit will experience in the actual use environment with all thermal solutions attached. Establish the ramp rate that a unit may experience during on/off cycles in use. Establish the dwell time at peak temperature. Cycle the unit until fail or until the expected end of life for the product. Temperature and continuity are monitored continuously during the test. Changes in temperature indicate degradation or failure of the thermal solution, continuity failures indicate failure of the part. Linear extrapolations of temperature sensor data should be used to predict thermal solution lifetimes.

## **SHOCK AND VIBRATION**

Shock and vibration testing are non-accelerated tests of the mechanical integrity of the package and /or assembly. Units need to be fixtured similar to the actual use condition to ensure the fixturing does not introduce unwanted stresses. Following establishment of the acceleration limits (in terms of g's of acceleration), units are tested to that limit as the minimum. Ideally, testing should also be performed in increasing increments beyond the g limit expectation until failure of the assembly, thus establishing the upper limit for the technology.

## Temp. - Humidity - Bias Application Example:



Use Arrhenius  
since RH constant at 85%

$$t_{\text{equiv}} = t_{\text{use}} \bullet e^{\left[ \frac{E_a}{kT} \left( \frac{1}{T_{\text{stress}}} - \frac{1}{T_{\text{use}}} \right) \right]}$$

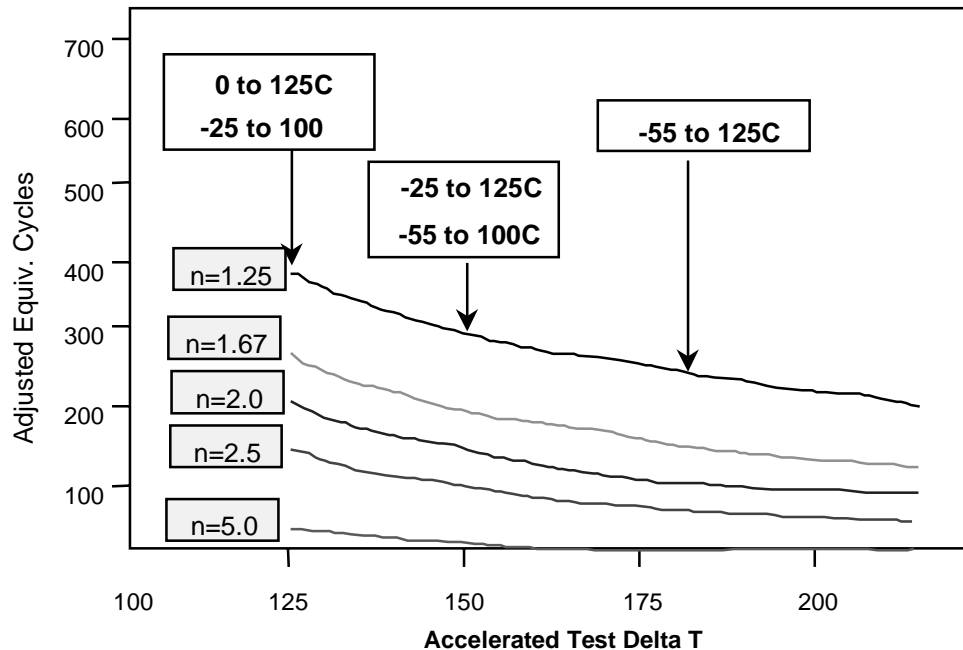
### Assumptions

- Use Condition:
  - 62,000 hrs.
  - 30C / 85% RH

### Relevant Mechanisms

FM #1: 1.4 eV  
FM #2: 0.75 eV

## Thermal Cycling Application Example:



## Coffin-Manson (Power Law)

$$t_{equiv} = t_{use} \cdot \left[ \frac{\Delta T_{use}}{\Delta T_{stress}} \right]^n$$

## Assumptions

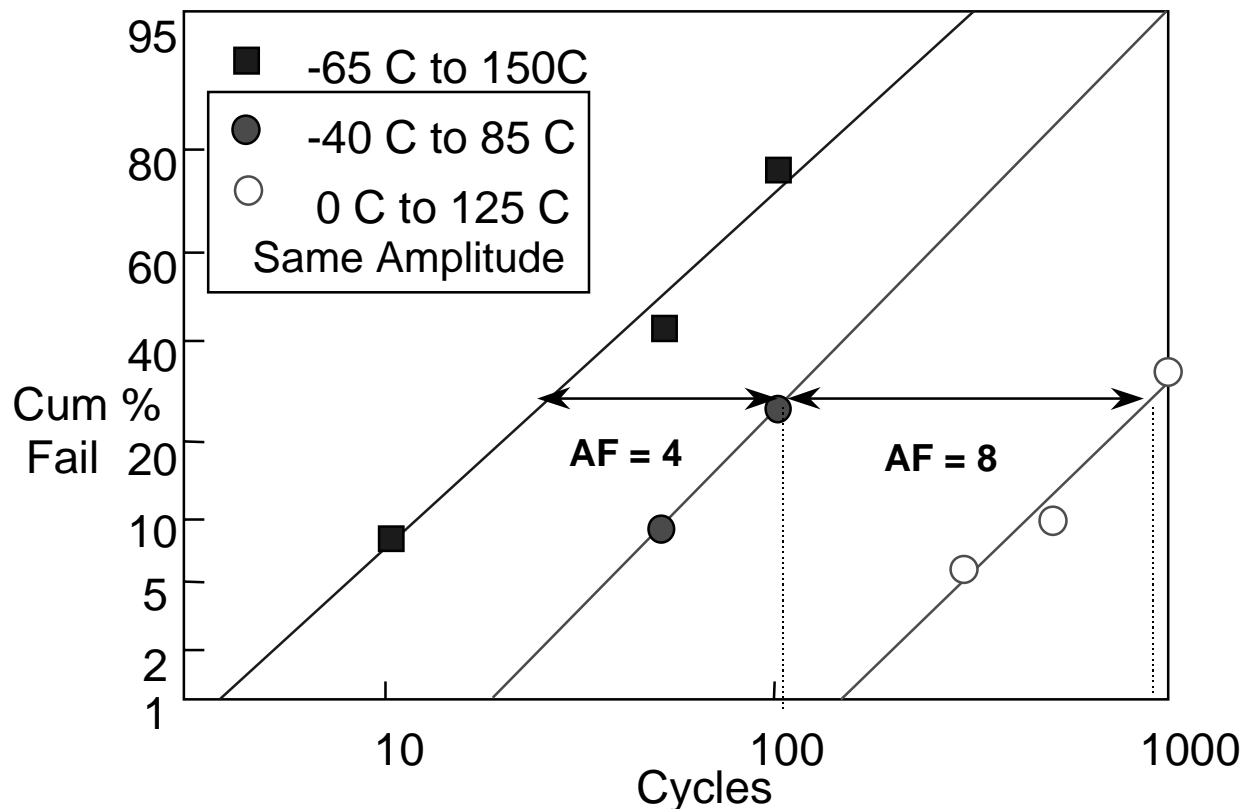
- Use Condition:
  - 1500 cycles
  - mean  $\Delta T$  40°C

## Relevant Mechanisms

- FM#1:  $n = 1.25$   
#2:  $n = 2.2$   
#3:  $n = 2$   
#4:  $n = 3$   
#5:  $n = 10$

## Thin Film Cracking in Plastic

- Coffin-Manson formula with  $\Delta T$  = maximum difference from **neutral stress** temperature (mold cure).
- For TC, the *low* temperature has the main effect in plastic packages.



$$AF = \left[ \frac{\Delta T_{\text{Stress}}}{\Delta T_{\text{use}}} \right]^n$$

$$n = \frac{\text{Ln}(AF)}{\text{Ln}\left(\frac{T_s}{T_{\text{Use}}}\right)}$$

Best Fit

$$n = 11$$

$$T_{\text{neu}} = 170 \text{ C}$$







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